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THE ROLE OF MICROTEXTURE OF FATIGUE LIFETIME VARIABILITY AND CRACK INITIATION MECHANISMS (PREPRINT)

Christopher J. Szczepanski

Universal Technology Corporation

S. Lee Semiatin and James M. Larsen

Metals Branch
Metals, Ceramics & Nondestructive Evaluation Division

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Commercial titanium alloys have demonstrated a fatigue lifetime debit in material that contains microtextured regions, as compared to material that has been processed to reduce microtexture. This result has generated commercial incentive to identify the effectiveness of various thermomechanical processing steps to remove microtexture and to determine the fatigue crack initiation mechanism in these microtextured regions. To quantify the efficacy of microtexture reduction on the fatigue behavior of alpha + beta titanium alloys, three different microstructural conditions of Ti-6Al-4V have been produced via distinct thermomechanical processing routes: an equiaxed alpha microstructure containing microtexture, an equiaxed alpha microstructure free of microtexture, and a beta annealed structure. The impact of sample orientation on fatigue behavior was examined by testing specimens along three different directions relative to the original plate reference frame; the rolling direction, the transverse direction, and 45° from the rolling direction for each of these microstructural conditions.

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The role of microtexture on fatigue lifetime variability and crack initiation mechanisms

Christopher J. Szczepanski[1], S. Lee Semiatin, and James M. Larsen

US Air Force Research Laboratory, Wright-Patterson Air Force Base, OH 45433 USA
[1]Universal Technology Corporation, Dayton, OH 45432 USA

Commercial titanium alloys have demonstrated a fatigue lifetime debit in material that contains microtextured regions, as compared to material that has been processed to reduce microtexture. This result has generated commercial incentive to identify the effectiveness of various thermomechanical processing steps to remove microtexture and to determine the fatigue crack initiation mechanism in these microtextured regions. To quantify the efficacy of microtexture reduction on the fatigue behavior of alpha + beta titanium alloys, three different microstructural conditions of Ti-6Al-4V have been produced via distinct thermomechanical processing routes: an equiaxed alpha microstructure containing microtexture, an equiaxed alpha microstructure free of microtexture, and a beta annealed structure. The impact of sample orientation on fatigue behavior was examined by testing specimens along three different directions relative to the original plate reference frame; the rolling direction, the transverse direction, and 45° from the rolling direction for each of these microstructural conditions. The mechanism of fatigue crack initiation will be discussed with regard to microstructural condition (processing history) and sample orientation. The distributions of fatigue lifetimes will also be characterized based on processing condition to determine if the presence of microtexture significantly impacts fatigue lifetime variability.

Keywords: *microtexture, thermomechanical processing, fatigue crack initiation, fatigue lifetime distribution*

1. Introduction

The deleterious influence of microtexture has been reported in numerous α and α + β titanium alloys under conditions of both continuous and dwell fatigue loading.[1-4] Characterization of the microstructure in neighborhoods of fatigue crack initiation sites by numerous researchers has led to the development of phenomenological models for fatigue crack initiation.[5-6] Despite this careful characterization, many reports appear to focus on the characterization of one representative sample. This approach may be misleading since microtexture cannot properly be treated as a single microstructural feature, rather regions of microtexture vary in intensity and in spatial distribution. Thus, it is reasonable to expect that a range of lifetimes should result from a population of microtextured regions with a distribution of properties. Furthermore, the aerospace design community must incorporate the minimum fatigue lifetime properties into their component lifing approaches and these minimum properties are known to diverge from the average properties as function of applied stress, temperature, and microstructure.[7]

The impact of changing the distribution of microstructural features on the fatigue behavior as a function of microstructure has been reported in the literature for other alloy systems.[7,8] Specifically, Brogdon and coworkers explored the impact of a refined grain size on the fatigue behavior of Waspaloy. As one would expect, the distribution of lifetimes observed was shifted as a function of microstructure. However, the minimum lifetimes were not significantly changed due to the refined grain size. The observation of minimum fatigue lifetimes was attributed to the remnant large grains within the microstructure. Similarly, Jha et al. accurately predicted a range of minimum fatigue lifetimes using a measured distribution of non-metallic particles, which are known to be the fatigue life-limiting defects in the powder nickel alloys they investigated.[8]

Texture evolution or removal of microtexture can also be viewed within a life prediction framework. Much time and effort has been spent to mitigate the formation of microtextured regions during primary and secondary forging processes. However, if one considers that fatigue is an inherently weak link process, it is clear that any remaining microtextured regions within a sample may deleteriously affect fatigue lifetimes. Furthermore, scaling this fact from lab scale specimens up to rotating components, it quickly becomes clear that removing all microtextured material from a system or fleet of systems is untenable and cost prohibitive. Therefore, by understanding the role that microtexture plays in determining minimum fatigue properties, it is possible to quantify the value in reducing microtexture from components and to appropriately manage the life limits on legacy systems. The current paper addresses some of these issues from a conceptual perspective and some initial data are presented to demonstrate the relationship between microtexture and minimum observed fatigue properties.

2. Experimental Procedure

2.1 Material and Thermomechanical Processing

The material investigated in this work was Ti-6Al-4V plate material with an initial thickness of approximately 32 mm. The as received plate comprised strong microtextured bands of α_p particles. These bands were a approximately 200 μm thick, with some bands as thick as 400 μm thick. Bands were typically 3-5 millimeters long as shown in the IPF map in Figure 1. A series of thermomechanical rolling processes were formulated and completed in house. These rolling trials were completed at a range of temperatures(955, 899, 815°C) and various strain paths(unidirectional along RD, unidirectional along TD,

and cross rolling) relative to the original rolling direction imposed in the as received material. All workpieces were rolled to a final target thickness of approximately 7 mm, corresponding to a part reduction of approximately 60%. Workpieces were returned to the furnace for 3 minute reheats after each rolling pass to insure uniform temperature of the workpiece throughout the rolling process.
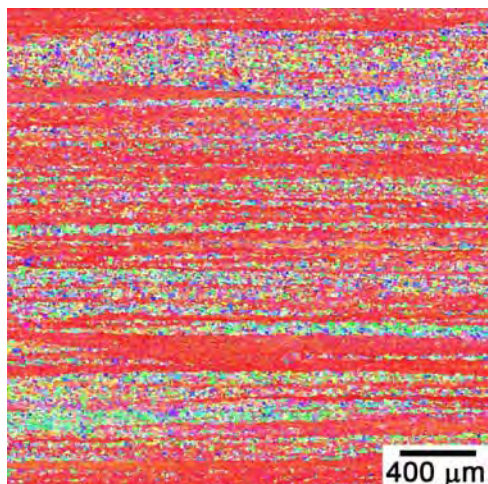

Figure 1. An inverse pole figure (IPF) map of the starting material. Strong bands of microtexture are visible in this RD-ND section.

2.2 Mechanical Testing

Cylindrical blanks for specimen machining were extracted from these batches of material along the RD, TD and 45° orientations. Tensile and fatigue testing was completed on specimens with a cylindrical gage 12 mm long and 4 mm in diameter using an MTS servohydraulic testing frame. All tests were completed at room temperature in laboratory air on electropolished specimens. An extensometer was employed on all specimens to measure strain in both tensile and fatigue tests. Tensile tests were conducted using strain rates of approximately 10^{-4} sec^{-1}. Fatigue tests were completed in load control at 30 Hz and a stress ratio of 0.1, with a maximum stress of 720 MPa.

Microstructure characterization was completed using an FEI XL30 FEG equipped with an EDAX TSL Hikari camera. The microscope was operated with a 10 nA probe current and a 20 kV accelerating voltage. A code developed in-house was employed to operate the microscope in a stage controlled mode to enable acquisition of EBSD data over 5-10 millimeter sized length scales.

3. Results and Discussion

3.1 Thermomechanical Processing

From the range of rolling trials investigated, two processes were identified that corresponded to high and low levels of microtexture. Representative IPF maps of the high and low microtexture conditions are shown in Figure 2a and 2b, respectively. The material with high levels of microtexture was achieved by cross rolling at 955°C. These

processing conditions yielded microtextured bands approximately 100 μm thick that were quite intense, but were isolated from one another. The low microtexture condition was produced by unidirectional rolling along the original TD. However, the deformation was sequentially imposed at three different temperatures in coming down through the α + β two-phase region. Further details of the thermomechanical processing trials can be found elsewhere.[9]
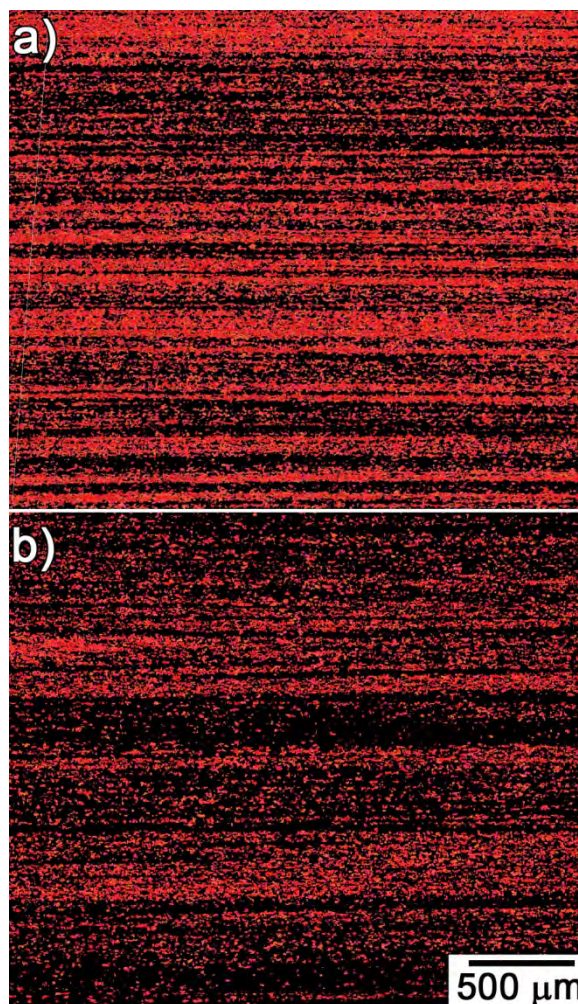

Figure 2. IPF maps of the materials with (a) high and (b) low levels of microtexture produced via thermomechanical processing.

After the thermomechanical processing was completed, heat treatments were completed to achieve uniform microstructural morphologies and volume fraction of α independent of the level of microtexture. Backscattered electron (BSE) micrographs of the resulting microstructures are shown in Figure 3 from which it is apparent that two of the microstructures (A and C) have nominally similar grain sizes and are composed of equiaxed α with some transformed product. Microstructures A and C were achieved by soaking the microtextured and randomly textured samples at 927°C for one hour followed by an argon quench. This material was ultimately given a one

hour stress relieving annealing step at 704°C for two hours followed by an argon quench to room temperature. Microstructure B was subjected to a β heat treatment by heating plates from the microtextured condition to approximately 10°C above the β transus for 5 minutes and then argon quenching to 732°C for two hours and finally quenched to room temperature.

3.2 Mechanical Properties

The monotonic loading properties are summarized in Figure 4 for each of the microstructures and specimen orientations investigated in this work. Loading along the original plate TD led to the highest yield strength and elastic modulus in all microstructures. In microstructure A and to a lesser extent in microstructure C, there are many α_p grains with their c-axis aligned with the original plate TD. This observation correlates with the fact that the highest mechanical properties are measured from specimens loaded along this direction.

Fatigue lifetimes are shown on a cumulative distribution plot in Figure 5. Specimens from all microstructures that were machined along a 45° orientation with respect to the original rolling direction are included in this plot. This orientation exhibited the shortest fatigue lifetimes out of the orientations tested in this work, which is expected given the crystallographic orientation of the microtextured bands in these samples. Specimens extracted from the 45° orientation would be expected to activate either basal or prism slip of grains within the microtextured bands.

Interestingly, there is not much difference in the minimum lifetimes observed in these specimens, which is on the order of 3×10^4 - 5×10^4 in each case. This result may be partially affected by the fact that fatigue tests were completed at a maximum stress of 720 MPa. This stress level was held constant for all specimens and orientations tested, which represented a high proportion of the yield stress in these specimens (i.e. ~0.85 σ_{YS}). Thus, part of the confounding influence in these results is that a substantial portion of these fatigue lifetimes can be attributed to the fatigue crack growth processes in these specimens.

Fatigue lifetimes were plotted on a cumulative distribution plot to evaluate the variation in fatigue lifetime distributions for each of the microstructural conditions investigated. One would expect less scatter in fatigue lifetimes for microstructural conditions where the distribution in microstructural features is more tightly controlled. This trend appears to be true if one compares the scatter in lifetime between the equiaxed microstructures (A and C) with the scatter in lifetimes observed in microstructure B. As expected, the scatter in fatigue lifetime is much more significant for microstructure B, which has a more random texture and much more random grain/colony size as compared with microstructures A and C.

Given the thermomechanical processing techniques employed to affect the microtexture of these samples, it is surprising that there is a negligible difference in the fatigue lifetime distribution of microstructures A and C. As discussed earlier, if the distribution of worst case microstructural features was altered by thermomechanical processing, that should be manifested as a difference in the slopes of the fatigue lifetime distributions. The lack of an apparent effect in these two microstructures could result from two factors. Either the thermomechanical processing steps employed here did not affect the distribution of critical microstructural features, or the regime in which testing was completed may not have exacerbated the difference in microstructure. In other words, in this regime of fatigue lifetimes, fatigue cracks would be expected to initiate early in life and most of the specimen lifetime is anticipated to be spent propagating fatigue cracks. If the majority of lifetime is spent in crack propagation, it would be expected that the lifetimes of these specimens should be similar since the microstructural morphologies of these batches of material are not significantly different.

If one considers the average lifetime of specimens extracted from these various batches of material, as
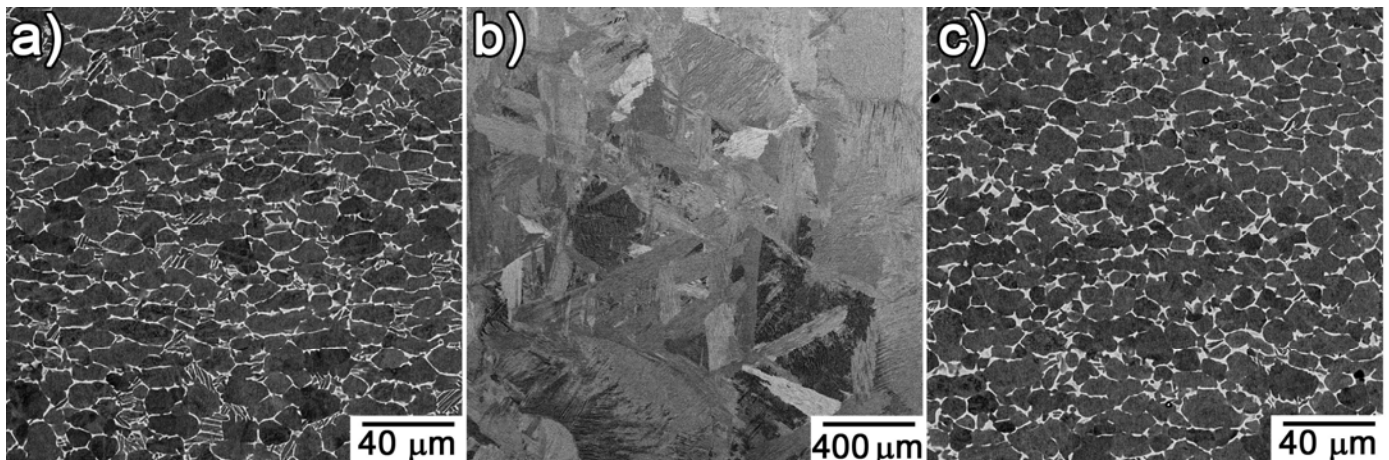

Figure 3. Backscattered electron (BSE) micrographs of the microstructural conditions. Microstructures A (a) and C (c) exhibit similar equiaxed α morphologies with little transformed product. Microstructure B (b) exhibits a β annealed microstructure.

represented by the 50 pct probability of failure point on the plot in Figure 5, a slight trend with respect to local texture and relative texture intensities may be apparent. Microstructure A, which had the most severe microtextured regions, exhibited the lowest average fatigue lifetime. Microstructure C, exhibited a slightly longer average fatigue lifetime. Microstructure B had the longest average lifetime which would be expected given the fact that the local textures within specific regions are much more random as compared with the previous two microstructural conditions. It is possible that the longer lifetimes observed in microstructure B results from improved crack growth resistance for this microstructure relative to the other microstructural conditions investigated.
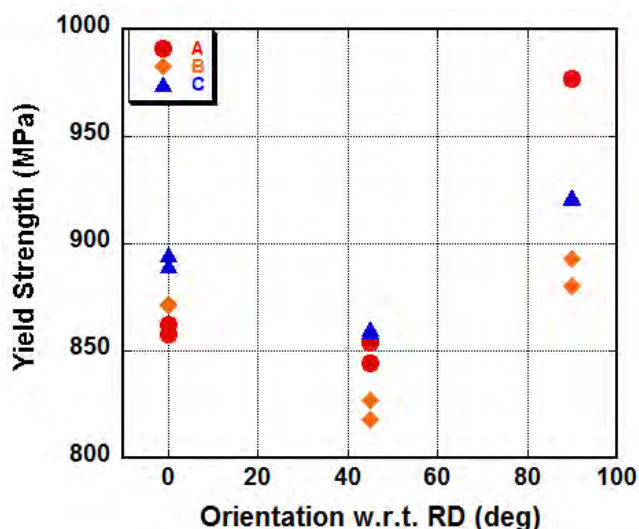

Figure 4. Yield strengths measured as a function of orientation for each of the microstructural conditions.
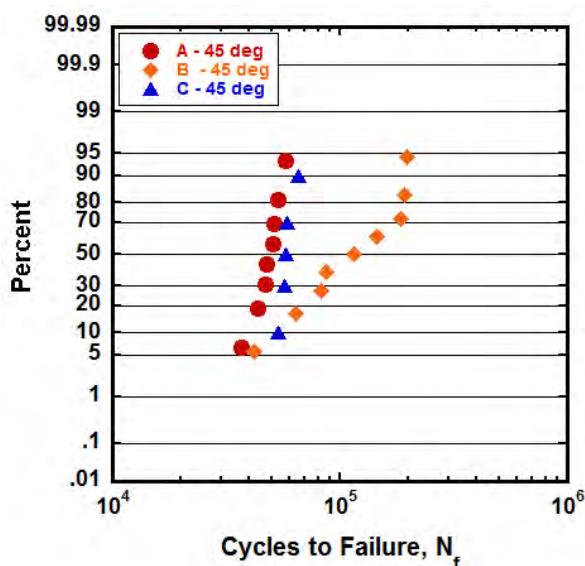

Figure 5. CDF of the fatigue lifetimes measured for specimens extracted 45° from the rolling axis for each of the microstructural conditions.

4. Summary and Conclusions

In this work, thermomechanical processing trials have been investigated for the purpose of determining the most effective means for reducing or eliminating microtexture in a commercial alloy. It was found that the most effective path for removing microtexture was to thermomechanically process the material at multiple temperatures in the α+β phase field. Additionally, by imposing strain along a direction perpendicular to the original rolling direction for this material, it was possible to reduce the size and intensity of the microtextured bands while also reducing the overall texture.

Despite this reduction in texture, no improvement in minimum fatigue lifetimes was observed. However, improvements in average fatigue lifetimes were observed as the intensity and size of the microtextured bands was decreased. For the β annealed condition (microstructure B), the distribution in fatigue lifetimes was significantly altered relative to microstructures A and C. The much longer average lifetimes observed in this alloy may result from improved fatigue propagation resistance, which is an area for further investigation.

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